REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
9/01/12

2. REPORT TYPE
Final Performance Report

3. DATES COVERED *(From - To)*
1/15/04-1/14/12

4. TITLE AND SUBTITLE
MURI: Novel Devices for Plasmonic and Nanophotonic Networks:

Exploiting X-ray Wavelengths at Optical Frequencies

5a. CONTRACT NUMBER

5b. GRANT NUMBER
FA9550-04-1-0434

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
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5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
California Institute of Technology
1200 E. California Blvd.
Pasadena, CA 91125

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
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Arlington, VA 22203

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10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT

: Approved for public release. Distribution is unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT
This final report summarizes the Caltech Plasmonics MURI program accomplishments. It is no exaggeration to say that the FY04 Plasmonics MURI catalyzed a worldwide research effort in which MURI investigators were research leaders of the plasmonics field from 2004-2010. In the MURI program, a large number of new concepts and devices were conceived, designed and demonstrated, including subwavelength waveguides, negative refractive index materials at visible frequencies, a far-field hyperlens, a plasMOStor plasmonic modulator, deep subwavelength plasmon lasers as well as larger plasmon lasers; laser antennas, plasmonic hyperspectral infrared detectors, to name a subset of achievements. Under MURI support, a total of 65 journal publications were published, including 2 papers in Nature, 2 in Nature Materials, 4 in Nature Photonics, and 2 in Science.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			19b. TELEPHONE NUMBER *(include area code)*

Summary Overview:

This final report summarizes the activities of the FY04 Plasmonics MURI, which is now concluded. It is no exaggeration to say that the FY04 Plasmonics MURI catalyzed a worldwide research effort in which MURI investigators were research leaders of the plasmonics field from 2004-2010. In the MURI program, a large number of new concepts and devices were conceived, designed and demonstrated, including subwavelength waveguides, negative refractive index materials at visible frequencies, a far-field hyperlens, a plasMOStor plasmonic modulator, deep subwavelength plasmon lasers as well as larger plasmon lasers; laser antennas, plasmonic hyperspectral infrared detectors, to name only a subset of achievements.

Under MURI support, a total of 65 journal publications were published, including 2 papers in Nature, 2 in Nature Materials, 4 in Nature Photonics, and 2 in Science. MURI Principal Investigator Harry Atwater wrote an article for Scientific American in April 2007 entitled "The Promise of Plasmonics" which sold >500,000 copies and was translated into 8 languages, and was subsequently reprinted in Scientific American's focus issue on Nanoscience. Professor Atwater also served as Principal Editor for a special issue on plasmonics of the IEEE Journal of Selected Topics in Quantum Electronics.

In addition to the research itself, in July 2005, MURI Investigators Albert Polman and Harry Atwater founded a Gordon Research Conference on Plasmonics, which was held for the first time July 23-28, 2006 at Keene State College, and subsequently in 2008 and 2010. In 2006 and 2008, the conference oversubscribed the attendance limit of 120 conferees and was ranked the highest among physical science Gordon Conferences for scientific quality by the attendees.

The research activities and publications of the Caltech Plasmonics MURI can be found at the webpage http://www.plasmonmuri.caltech.edu/ (password for members only section of this site available to AFOSR personnel upon request; please email Harry Atwater at haa@caltech.edu)

Scientific and Technical Highlights:

Period 1:

The MURI program began in June 2004, and initial effort focused on development of materials and electromagnetic designs for plasmonic devices. The kick-off meeting was held in October 2004 at the California Institute of Technology. The principal investigators recruited students and post-docs who carried out the bulk of the experimental effort of the MURI program, and met regularly by teleconference and face-to-face meetings. The initial effort included experimental research on imaging and spectroscopy to observe light emission, optical guiding, and is complemented by theoretical work and simulation of plasmon propagation in metallodielectric structures. Highlights over Period 1 included:

- Plasmon-enhanced light emission from InGaN quantum wells
- Integration of plasmon and dielectric waveguides, and coupling between them.
- Theoretical investigation of propagation, dispersion and loss in plasmon waveguides.
- Observation of large spectral birefringence in photo-addressable polymers.

Period 2:

Period 2 was a phase of prolific and extensive development of plasmonic components by the MURI team. A number of "firsts" that are highlighted below were achieved during this Period. In almost every case, not only was a new plasmonic concept introduced, but was also reduced to experimental practice.

Highlights over Period 2 include realization of:

- Plasmon hyperspectral InAs DWELL detectors with metallic photonic crystal contacts that show enhanced spectral detectivity and tunability for mid- infrared wavelength detection. The generation-recombination limited D* at 77K with a 300K background is a factor of 20 higher than that of the control sample, and the BLIP temperature of the DWELL PE detector is raised by 20% in comparison to control samples
- Plasmon slot waveguides: design, simulation and experimental verification of propagation with modes that < 10% of free space modal cross section.
- Plasmon-enhanced light emission from Si quantum dots; 8x increase in intensity obtained; the increased intensity is shown to be due to an enhanced radiative emission rate.
- Plasmonic laser antennas fabricated in which enhanced emission is generated from the end facets of edge-emitting lasers by emitting through wavelength-scale and subwavelength-scale apertures.
- A tunable plasmonic lens in which the in-plane focal position for the surface plasmon mode is changeable by altering the angle of the incident beam.
- Field effect electroluminescence from Si; this is a newly-discovered electroluminescence mechanism that enables efficient electrical generation of excitons in quantum dots embedded within a field effect transistor.

Period 3:

Period 3 was a phase of extremely productive design and realization of plasmonic components by the MURI team. Several "firsts" that occurred during Period 3 are highlighted below. In each case, a new plasmonic concept introduced and was also reduced to experimental practice.

Highlights over Period 3 include realization of:

- Visible Frequency Negative Refraction – first report of negative refraction and negative index at visible frequencies
- Improved Plasmonic Laser Antenna – quantitative comparison of experiment and theory for near field of near infrared laser antenna
- Record High Q for Plasmonic Cavity – toroidal plasmonic microresonator with Q factor of 400, a record for a plasmonic resonator.
- Plasmonic Nanoresonators for Raman Enhancement
- Plasmon Enhanced Emission from Semiconductor Quantum Dots – investigation of enhanced emission from CdSe quantum dots in proximity to metal surfaces and discontinuous films
- Identified Limit to Light Localization in Plasmonic Structures

Period 4:

Period 4 was a phase of prolific and extensive development of plasmonic components by the MURI team. A number of "firsts" that are highlighted below were achieved during this Period. In almost every case, not only was a new plasmonic concept introduced, but was also reduced to experimental practice.

Highlights over Period 4 include realization of:

- Plasmon hyperspectral InAs DWELL detectors with metallic photonic crystal contacts that show enhanced spectral detectivity and tunability for mid- infrared wavelength detection. The generation-recombination limited D* at 77K with a 300K background is a factor of 20 higher than that of the control sample, and the BLIP temperature of the DWELL PE detector is raised by 20% in comparison to control samples

- Plasmon slot waveguides: design, simulation and experimental verification of propagation with modes that < 10% of free space modal cross section.
- Plasmon-enhanced light emission from Si quantum dots; 8x increase in intensity obtained; the increased intensity is shown to be due to an enhanced radiative emission rate.
- Plasmonic laser antennas fabricated in which enhanced emission is generated from the end facets of edge-emitting lasers by emitting through wavelength-scale and subwavelength-scale apertures.
- A tunable plasmonic lens in which the in-plane focal position for the surface plasmon mode is changeable by altering the angle of the incident beam.
- Quantum dot microtoroidal laser with world record low threshold; a record low turn-on energy (less than 10 femto Joules) was measured, corresponding to a continuous wave operation threshold of 660 nanoWatts.

Period 5:

Period 5 was a phase of prolific and extensive development of plasmonic components by the MURI team. A number of "firsts" highlighted below were achieved during this Period, the most notable of which is the report of a deep subwavelength plasmonic laser. In almost every case, not only was a new plasmonic concept introduced, but was also reduced to experimental practice.

- We demonstrated deep sub-wavelength plasmonic lasers at visible frequencies using semiconductor materials for the first time. This breakthrough now suggests new sources that may produce coherent light far below the diffraction limit. We have shown that extremely strong mode confinement and the ensuing preferential coupling to the laser mode are key aspects of plasmonic lasers. We have also shown that the advantage of plasmonic lasers is their ability to downscale the physical size of devices, as well as the optical modes they contain, unlike conventional diffraction-limited lasers. Furthermore, the use of metals in plasmonics could provide a natural route towards electrical injection schemes that do not interfere with mode confinement. The impact of plasmonic lasers on optoelectronics integration is potentially significant because the optical fields of these devices rival the smallest commercial transistor gate sizes and thereby reconcile the length scales of electronics and optics.
- We demonstrated a high-Q SPP whispering-gallery microcavity that is made by coating the surface of a silica microresonator with a thin layer of a noble metal. Using this structure, Q factors > 1000 can be achieved in the near infrared for surface-plasmonic whispering-gallery modes at room temperature. This nearly ideal value, which is close to the theoretical metal-loss-limited Q factor, is attributed to the suppression and minimization of radiation and scattering losses that are made possible by the geometrical structure and the fabrication method. The SPP eigenmodes are confined within the whispering-gallery microcavity and accessed evanescently using a single strand of low-loss, tapered optical waveguide, which allows a high coupling efficiency. The demonstration of high-Q surface-plasmonic microcavities opens many possibilities for applications in fields ranging from fundamental science to device engineering.
- We have shown that chemical electroplating and controlled thin film metal deposition can yield high aspect ratio metal fins capable of efficient surface plasmon reflection. We showed that two closely spaced fins define a Fabry-Perot nano-cavity that concentrates surface plasmon polaritons at visible frequencies with Q-factors as high as 200. A simple analytical model describes the observed results well when accounting for the surface plasmon dispersion and the effect of scattering and reflection from the metal fins. Concurrent high quality factors and sub-wavelength mode volumes would allow a strong Purcell effect competitive with diffraction limited photonic crystal cavities and enables numerous applications such as fast and efficient light emitting devices.

Personnel Supported:

Faculty: Dr. Harry A. Atwater, Dr. Axel Scherer, Dr. Oskar J. Painter, Dr. Kerry J. Vahala, Dr. Federico Capasso, Dr. Eli Yablonovitch, Dr. Xiang Zhang and Dr. David R. Smith
Research Scientist: Dr. Henri Lezec, Caltech
Postdocs: Alois Degiron, Domenico Pacifici, R. Colombelli, Ert Cubukcu, Mladen Barbic, Bumki Min, Lan Yang, Dentcho A. Genov, David F. P. Pile, Rupert Oulton, Xuejin Zhang, Dongmin Wu, Mariano Troccoli
Graduate Students: Caltech: Stanley Burgos, Matthew Dicken, Kenneth Diest, Gerald Miller Chris Walker, Ting Hong, Raviv Perahia, Orion Crisafulli, Luke A. Sweatlock, Jennifer A. Dionne (partial), Carrie E. Ross (partial), Julie Biteen, Michael Hochberg, Terrell Neal, T.Baehr-Jones, Kouichi Okamoto, Jiming Bao, Eric Ostby, Lan Yang, Thomas Johnson, Paul Barclay, Matt Eichenfeld, Jessie Rosenberg (Partial) UCLA: Hyojune Lee, Matteo Staffaroni, Japeck Tang, Shantha Vedantam; UC Berkeley: Jennifer Steele, Volker Sorger, Zhaowei Liu, Hyesog Lee, Sheng Wang, Yi Yong, H. Liu, Harvard: Ert Cubukcu, FOM: Hans Mertens, Duke: Claudio Dellagiacoma.

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65. Room-temperature sub-diffraction-limited plasmon laser by total internal reflection Ma, Ren-Min; Oulton, Rupert F.; Sorger, Volker J.; G. Bartal and X. Zhang, NATURE MATERIALS Volume: 10 Issue: 2 Pages: 110-113 Published: FEB 2011.

a. Invited Conference and Seminar Presentations

Over 300 invited presentations were made by the PIs during the MURI grant period, including more than 2 dozen plenary and keynote lectures in international conferences (list of individual presentations contained in performance reports)

b. Consultative and Advisory Functions

Professor Harry Atwater, P.I., California Institute of Technology

Presenter and participant in DARPA Meeting on Photonics for Quantum Information Technology, Los Angeles, CA, 1/21/05

Informal consultant to DARPA program managers (S. Wolf, D. Healey, V. Browning, H. Temkin and R. Athale) about the status of research in the plasmonics field.

Presentation to AFOSR Science Advisory Board during AFOSR program review, 7/19/05.

Founded Gordon Research Conference on Plasmonics in July 2005, to be held first in July 2006.

Principal Editor, IEEE Journal of Selected Topics in Quantum Electronics, special issue on Plasmonics and Surface Plasmon Photonics

Professor Xiang Zhang, University of California Berkeley

Co-Chair, 2005 NSF Nanoscale Science and Engineering Annual Grantee Conference, Washington DC, 2005
Panelist, 3rd International Symposium for Nano Manufacturing
Member of Executive Committee, Applied Science and Technology Graduate Program, UC Berkeley
Associate Editor, Journal of Nanoparticle Research
Member of Editorial Board, Journal of Nanoelectronics and Optoelectronics
Member of Editorial Board, Nano Research Letter

c. **Transitions**. none

d. **New Discoveries, Inventions, or Patent Disclosures**.

Professor Federico Capasso, Harvard University

Capasso, K. Crozier, E. Cubukcu, E. Kort, and N. Yu, "Active Optical Antenna" US Patent filed December 2005

Professor Oskar Painter, California Institute of Technology:

UNM-679 "High Performance Hyperspectral Detectors Using Photon Controlling Cavities," which was disclosed on July 26, 2004. The U.S. utility patent application No. 11/225,006 was filed on September 14, 2005.

Professors Kerry Vahala, Harry Atwater, Axel Scherer, California Institute of Technology:

Record turn-on energy quantum dot laser (less than 10 femto Joules).

Record continuous wave operation threshold (660 nanoWatts).

e. **Awards**

Professor Harry Atwater, California Institute of Technology
Joop Los Award and Fellowship, Dutch Foundation for Fundamental Research on Matter, 2005
Breakthrough Award, Popular Mechanics, 2010
Fred Kavli Distinguished Lectureship in Nanosciences, Materials Research Society, 2010

Professor Federico Capasso, Harvard University
King Faisal International Prize for Science, 2005.
Presidential Gold Medal for Achievements in the Sciences and in the Arts (Italy)
Edison Medal, Institute of Electrical and Electronic Engineers (IEEE), 2004
Arhur Schawlow Prize in Laser Science, American Physical Society, 2004
Tommasoni International Prize for Outstanding Achievements in Physics, 2004

Assistant Professor Oskar Painter, California Institute of Technology
Caltech GSC Mentoring Award, 2005.

Professor David R. Smith, Duke University
Thomson Reuters Citation Laureate
Co-recipient of the Descartes Research Prize, the most prestigious prize given by the European Union (December, 2005).

Stansell Research Award, given by the Pratt School of Engineering at Duke University (June, 2006).

Professor Xiang Zhang, University of California Berkeley
Chancellor's Professorship, UC Berkeley, 2004-2009.
Finalist for the 2005 Small Times Magazine Small Tech Best Researcher Award
AAAS Fellow
OSA Fellow
Prof. Xiang Zhang, along with students' work selected by *Time Magazine* as one of Top 10 Scientific Discoveries of 2008

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